A Physical Model to Determine Snowfall Over Land by Microwave Radiometry

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***Abstract*—Falling snow is an important component of global precipitation in extratropical regions. This paper describes the methodology and results of physically based retrievals of snow falling over land surfaces. Because microwave brightness temperatures emitted by snow-covered surfaces are highly variable, precipitating snow above such surfaces is difficult to observe using window channels that occur at low frequencies ($\nu < 100$ GHz). Furthermore, at frequencies $\nu \leq 37$ GHz, sensitivity to liquid hydrometeors is dominant. These problems are mitigated at high frequencies ($\nu > 100$ GHz) where water vapor screens the surface emission, and sensitivity to frozen hydrometeors is significant. However, the scattering effect of snowfall in the atmosphere at those higher frequencies is also impacted by water vapor in the upper atmosphere. The theory of scattering by randomly oriented dry snow particles at high microwave frequencies appears to be better described by regarding snow as a concatenation of "equivalent" ice spheres rather than as a sphere with the effective dielectric constant of an air–ice mixture. An equivalent sphere snow scattering model was validated against high-frequency attenuation measurements. Satellite-based high-frequency observations from an Advanced Microwave Sounding Unit (AMSU-B) instrument during the March 5–6, 2001 New England blizzard were used to retrieve snowfall over land. Vertical distributions of snow, temperature, and relative humidity profiles were derived from the Mesoscale Model (MM5) cloud model. Those data were applied and modified in a radiative transfer model that derived brightness temperatures consistent with the AMSU-B observations. The retrieved snowfall distribution was validated with radar reflectivity measurements obtained from a ground-based radar network.**

***Index Terms*—Electromagnetic scattering, estimation, millimeter-wave radiometry, remote sensing, satellite, snow.**

I. Introduction

MEASUREMENT of global precipitation is one of the goals of climate studies. Although most global precipitation occurs as rainfall, snowfall plays a significant role in the extratropical hydrological cycle. Snow, falling early in winter, can retard freezing of the underlying soil, thereby allowing subsequent melt water to penetrate the ground. Conversely, if the ground freezes because snow falls late in winter, flooding may ensue from run-off during the spring thaw. Snow also serves as a reservoir of water that can be released later in the year to support agriculture and hydroelectric power generation. Snowstorms can also be hazardous for transportation and other economic activities. One of the most important challenges for future satellites is to detect snowstorms from space. This paper presents a physical model of radiation at millimeter-wave frequencies that seeks to infer snowfall rates over land by taking advantage of water vapor screening to obscure the underlying snow-covered surface.

Midlatitude precipitation occurs in a wide variety of forms from snow to drizzle to rain and to hail [1]. Storm types include multicell and supercell thunderstorms, extratropical cyclones, and hurricanes. The well-developed techniques to study tropical precipitation, using frequencies ≤ 90 GHz, addressed rain occurring in nearly moist adiabatic environments. Extratropical cyclones are a completely different setting for precipitation than any type of tropical storm. Broad zones of frontal lifting produce broad sheets of clouds and precipitation that are mostly though not completely stratiform. These stratiform precipitation regions are similar microphysically to the stratiform regions of tropical mesoscale convective systems. However, the generally cooler conditions often produce a melting layer that is near the earth's surface. Under the coldest conditions, the precipitation reaches the surface as snow.

Most spaceborne remote sensing of snow has addressed the measurement of snow accumulation on the ground (see [2]). Snow within the atmosphere has mainly been derived from microwave radiometry over oceanic regions where the measurements were not affected by snow accumulated on the ground [3]–[6]. Furthermore, most of the snow considered in the above studies are frozen particles above the melting layer or anvil ice clouds, not snow falling at the surface. Because snow accumulation on land affects the emission properties of the surface, the measurement of snowfall within the atmosphere has been difficult with radiometers that operate at frequencies less than 100 GHz where the atmosphere is relatively transparent, and the sensitivity to frozen particles is lower than at higher frequencies. Snow falling over land has been derived from the brightness temperatures at frequencies where absorption occurs using empirical relationships by Kongoli *et al.* [7] and by Chen and Staelin [8]. Although such empirical relationships are operationally useful, physical models are needed to understand how the retrieved snowfall depends on the various ground and atmospheric factors that affect the measured brightness temperatures. To our knowledge, this is the first retrieval of snow falling over land based on a physical model.

The Advanced Microwave Sounding Units (AMSU-B) radiometers on the National Oceanic and Atmospheric Administration (NOAA) 15, 16, 17 spacecraft [9] have the channel set and resolution to resolve locally intense precipitation. The AMSU-B has a nominal 15-km-diameter footprint at nadir and provides observations at 89, 150, and 183 ± 1, ± 3, and ± 7 GHz.

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These channels are sensitive to both the water vapor (for surface screening) and the snow particles. The AMSU-B radiometer on NOAA 15 initially encountered radio frequency interference from onboard transmitters that were ultimately shut down in the autumn of 1999. Software fixes were encoded in late 1999 so that reliable spaceborne data at frequencies greater 100 GHz were available by January 2000. The NOAA 16 and 17 did not have problems with radio frequency interference. This paper presents a physical model that was used to derive snowfall over land from AMSU-B observations.

II. Case Study

The blizzard of March 5–6, 2001 presented a unique opportunity to observe intense snowfall over land. That blizzard was one of the more intense snow storms of the season, depositing on the order of 50 cm of snow on much of Vermont, New Hampshire, and northeastern New York State with several stations reporting that 75 cm were deposited for the day. Both the NOAA 15 and 16 satellites observed this blizzard (NOAA 17 was launched in June 2002). However, the best spatial and temporal coverage between available ground radar data and AMSU-B data was at 23:00 UTC with the NOAA 15 AMSU-B observations.

A. Radar Data

Fig. 1(a) shows a composite of the National Weather Service (NWS) operational weather radar reflectivity $Z_{\rm eff}$ (millimeters to the sixth power per cubic meter) obtained from several ground stations over the Northeastern United States on March 5, 2001 at 23:00 UTC. Note that the limited range of the radar data does not extend far over the ocean area [Fig. 1(a)]. The snowfall was greatest over Connecticut, Maine, Vermont, and New Hampshire. This composite of $Z_{\rm eff}$ is based on whichever of the lowest four antenna elevations yield the highest reflectivity. At ranges beyond 50 km from the radar, those elevation angles are usually 0.5°. The heights at which those reflectivities are measured varies with distance from the particular radar, falling between 0.5 and $\sim$ 2.5 km. Although the NWS operational radar data have well-known limitations, in the absence of a preplanned field observation campaign, they provide readily available observations to compare to snowfall derived from microwave brightness temperatures.

The radar reflectivity data were smoothed with a 16×16 km template to match the finest spatial resolution of the AMSU-B channels. The center points of the smoothed radar data matched those of the AMSU-B latitude and longitude center points for each footprint. The NWS radar reflectivity resolution is very fine, however, its latitude and longitude mapping was not precise (offsets by no more than 0.1°). Averaging the NWS image to the AMSU-B resolution tended to smooth any effects of location mismatch. The maximum reflectivity in the smoothed radar reflectivity data over the land is $\sim$37 dBZ. Depending on the relationships used to convert from logarithmic power (dBZ) to rainfall rate and then from rainfall rate to snowfall rate, this reflectivity can correspond to snowfall rates between 40 and 125 mm $\cdot$ h^{-1}, with the smaller numbers for wet snow that compresses the snow pack.

V. Discussion and Conclusion

A physically based retrieval algorithm was developed to estimate snowfall over land. The retrieval algorithm relied on a multiparameter cloud model to generate the vertical structure of a snow cloud, including snow mass, snow particle effective diameter, and water vapor. The MM5 cloud simulation was used to provide useful statistics for generating those cloud characteristics. Ground-based attenuation measurements were used to characterize the equivalent sphere snow particle size used herein. The snow cloud profile and surface emissivity were then used in radiative transfer calculations that were optimized against AMSU-B observations at 89, 150, and 183.3 $\pm$ 7, $\pm$3, and $\pm$1 GHz. For each pixel in the image, the multiparameter cloud parameterization that produced brightness temperatures that best fit the AMSU-B observations was selected as the retrieved profile. This paper demonstrated the following.

1) Microwave radiometric channels operating at frequencies greater than 89 GHz provide information on snowfall over variable land surfaces because the surface emissivity is screened by water vapor absorption at those frequencies.
2) An electromagnetic scattering model of randomly oriented snow particles was adequately represented as equivalent spheres whose diameters were mainly determined by the small dimensions of the snow particles as suggested by Grenfell and Warren [22]. That model accounted for measured values of attenuation per unit mass between 96 and 225 GHz. Inserting the G–W "equivalent" ice spheres in a delta-Eddington radiative transfer model yielded brightness temperatures at 89, 150, and 183 $\pm$ 1, $\pm$3, $\pm$7 GHz that were consistent with values measured by AMSU within $\pm \sim 5$ K. This was, in part, due to the fact that the diameters of the equivalent particles were small so that the asymmetry factor was also small (as might be expected from Rayleigh-like scattering). Small asymmetry factors reduce the transmission of snow layers, thereby achieving lower brightness temperatures than those produced by a low-density fluffy snow particle ice–air effective medium with larger asymmetry factors.
3) Weighting vectors illustrated the relationships between the physical properties of the clouds (snow and water vapor characteristics) and the resulting brightness temperatures.
4) Three variables used to adjust the snow mass, relative humidity, and surface emissivity were sufficient to estimate snowfall rates consistent with NWS radar reflectivity measurements and to yield a $Z_{\rm eff}$–R relationship that was consistent with others reported in the literature.

The number of retrieved parameters was kept to a minimum because there are only three to four degrees of freedom in the five AMSU-B channels. This paper emphasizes the need for a dedicated set of coincident observations that include microwave as well as microphysics measurements. Field campaigns are needed to measure the high-frequency electromagnetic properties of snow along with the habits of frozen hydrometeors to yield parameters that we were forced to derive from disparate observations. Such measurements need to include the *small* as well as the *large* dimensions of frozen hydrometeors. More realistic retrieval procedures can be developed when additional information becomes available.